Development of a Ground Multi-Mission Low-Cost Optical Terminal (LCOT) for Free-Space Optical Communications

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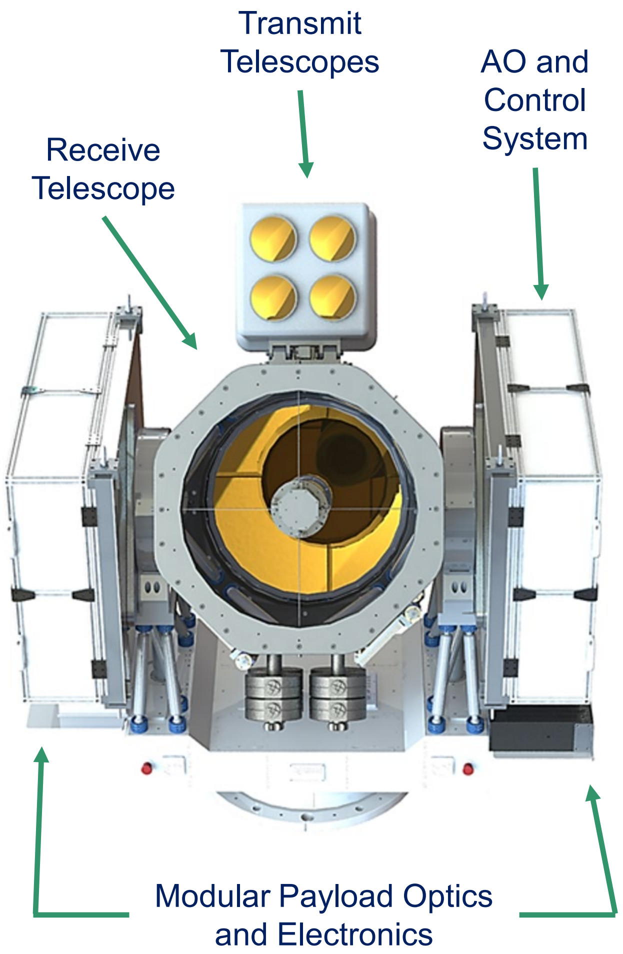
LCOT Program Objectives

- Design an optical communication ground system architecture with the flexibility to support a range of use cases while leveraging industry capabilities to the maximum extent possible
- Create a prototype for a modular, repeatable, multi-mission optical ground station
- Establish the infrastructure for proving and demonstrating advanced optical communications technologies and capabilities
- Cultivate a range of commercial vendors to provide specialized optical communications components
- Conduct experiments with optical communications flight projects to demonstrate evolving LCOT capabilities
- Collaborate with universities and other research entities to advance optical communication capabilities

LCOT System Description

- LCOT brings an unprecedented level of optical test capability to the Space Communication and Navigation (SCaN) and NASA
  - Modular, interchangeable optics, electro-optics, and modems
  - 70cm Receive aperture and custom gimbal for fast tracking and high stability with large receive area
  - Adaptive optics (AO) enables some technologies (esp. coherent and quantum comms) and improves the performance of all
  - Common test platform available for free space IR systems

LCOT Provides an Accessible, Powerful, and Affordable Platform for Optical Communication



- Current investments have provided telescope, AO, gimbal, infrastructure, and control software development
- Additional support of materials and personnel will:
  - Complete base LCOT system
  - Build and/or install following to support experiments with ground station including:
    - Transmitter telescope
    - Transceiver
    - Facility work
  - Prepare LCOT for future NASA, industry, and academia missions

LCOT Timeline

Built a shelter and 16' diameter dome at the Goddard Geophysical and Astronomical Observatory (GGAO)

Receiving non-coherent low rate optical comm

Received greenlight from SCaN to include adaptive optics, transmit telescopes, and modem

Receive Telescope Factory Acceptance Test (FAT) and Install

LCRD Phase A – Demonstration of AO capability for atmospheric conditions with downlink

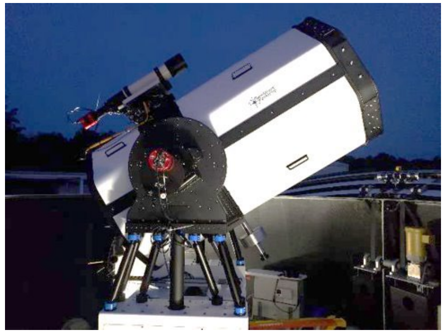
LCRD Phase C – Demonstration of the NFOV/FSM state machine and fine tracker. Establish connection with the LCOT SCPPM modem.

LCRD Comms

Calendar Year

2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026

Tracking LEO and GEO satellites



Received SCaN funding for large telescope to serve as an optical communications ground terminal.

Planewave Instruments (PWI) was selected to build a 70cm diameter telescope modified to meet the needs of optical communications

Received funding for Adaptive Optics (AO) and optical benches.

GuideStar was selected to develop AO system to meet need of optical communication. Design Interfaces Inc provide optics benches

Transmit Optical Assembly (XOA) Award

O2O Demo

LCRD Phase B – Demonstration of the Wide Field of View (WFOV)/Gimbal state machine and coarse tracker

Future coherent LEO, GEO, and lunar optical and quantum communication

LCOT System Reference (As installed at GGAO)

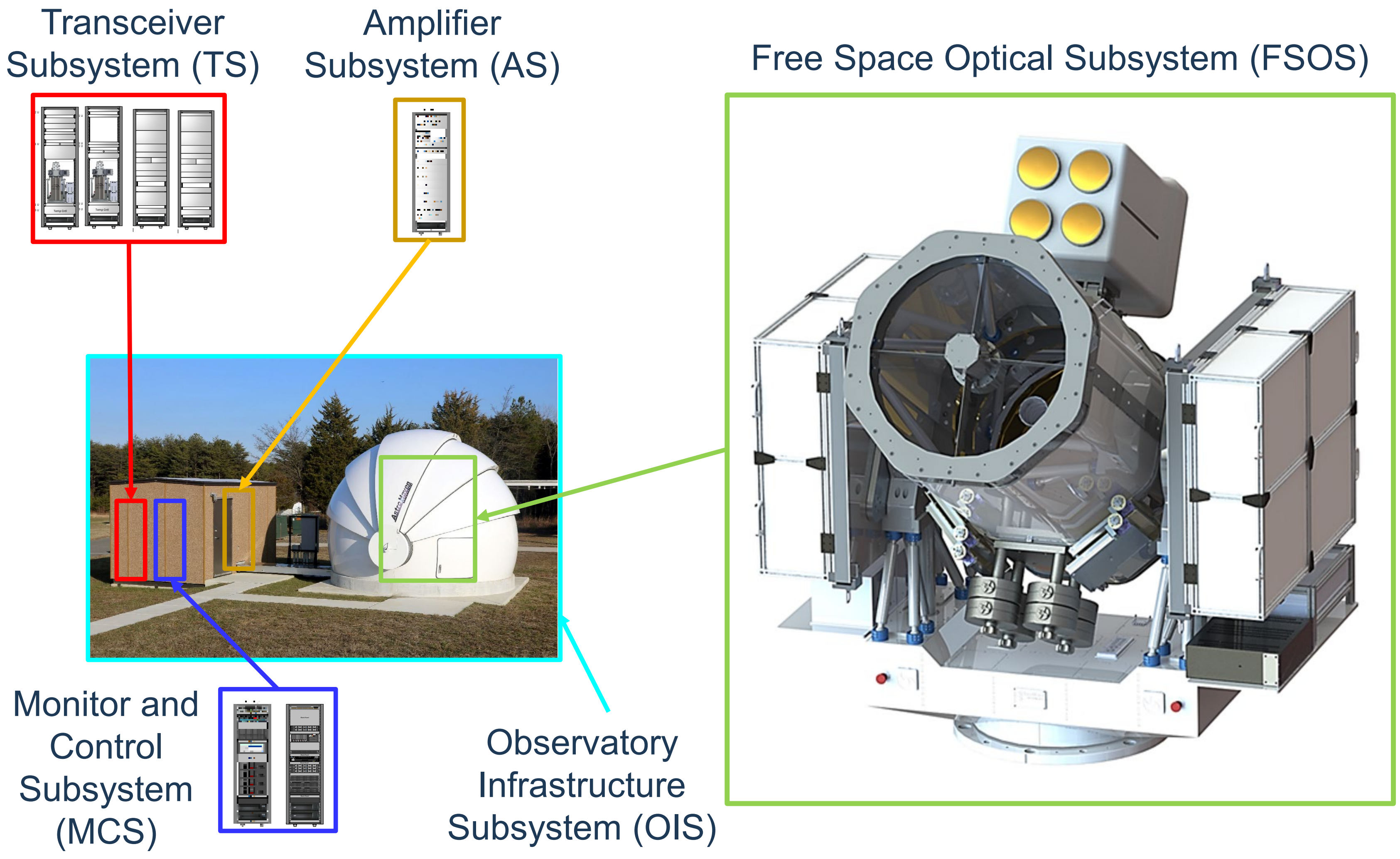
Free Space Optical Subsystem (FSOS):
Direct free space optical signals and hardware

Transceiver Subsystem (TS):
Interface with externally provided experimenter TSs

Amplifier Subsystem (AS):
Includes the amplifiers and associated electronics

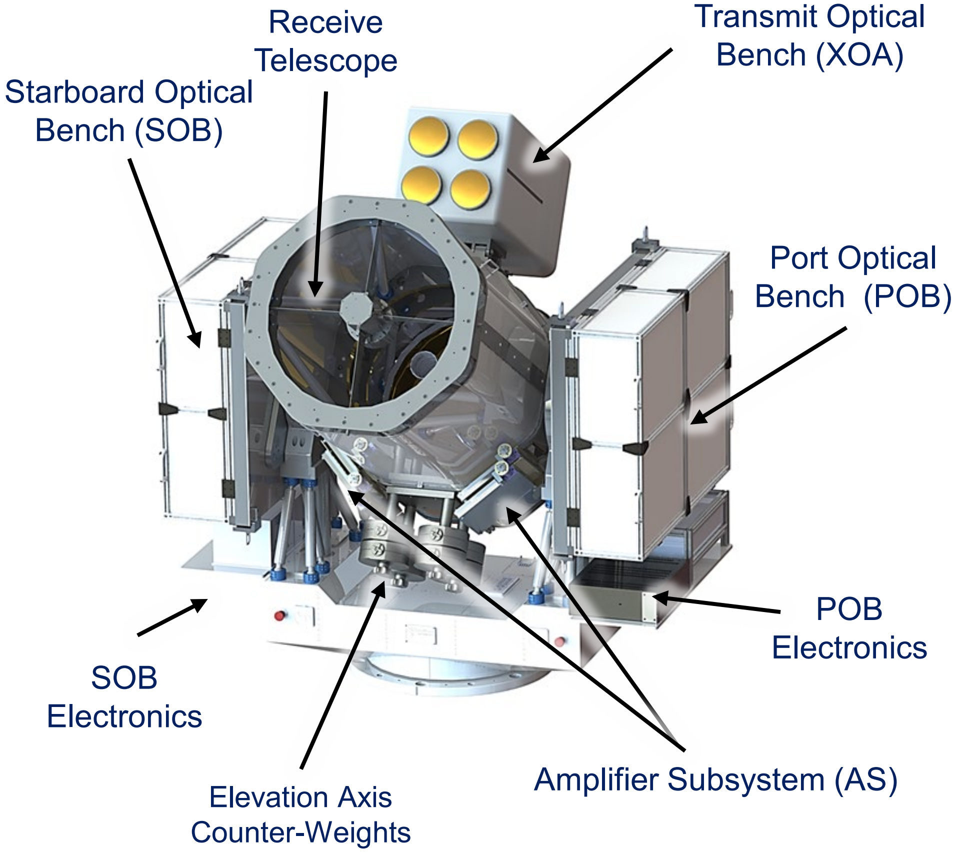
Monitor and Control Subsystem (MCS):
The MCS provides overall commanding, monitoring, and control for the other LCOT subsystems

Observatory Infrastructure Subsystem (OIS):
Infrastructure and supporting services



Free Space Optical Subassembly (FSOS)

- 70cm Planewave Instruments Telescope
  - Installed at GGAO in July 2021
  - Currently undergoing testing and integration as optical bench being assembled and tested in the lab
- Two Optical Benches mounted to the sides of receive telescope
  - Port Optical Bench with Adaptive Optics (AO)
    - Completed initial horizontal and vertical testing of AO in lab; Planned to be installed on the telescope in mid-2023
  - Alternatively, Starboard Optical Bench (SOB) will be configured to support missions with using Pulse Position Modulation (PPM)
- Transmit Optical Assembly (XOA)
  - Preliminary refractive transmit array design created by GSFC optical engineers
  - Partnered with University of Arizona to complete design; exploring next steps to initiate the build phase of the XOA
- Robotic Piggyback Mount (RPM)
  - XOA will be mounted on the RPM
  - The RPM is a computer-controlled tilt stage that compensates for misalignment between transmit and receive optical axes as telescope changes elevation angle
- One large task in progress is developing the software to allow the telescope to auto-track
- Once a downlink has been acquired, the tracking camera (on the optical bench) will be used to adjust telescope motion to keep the downlink centered in the field of view

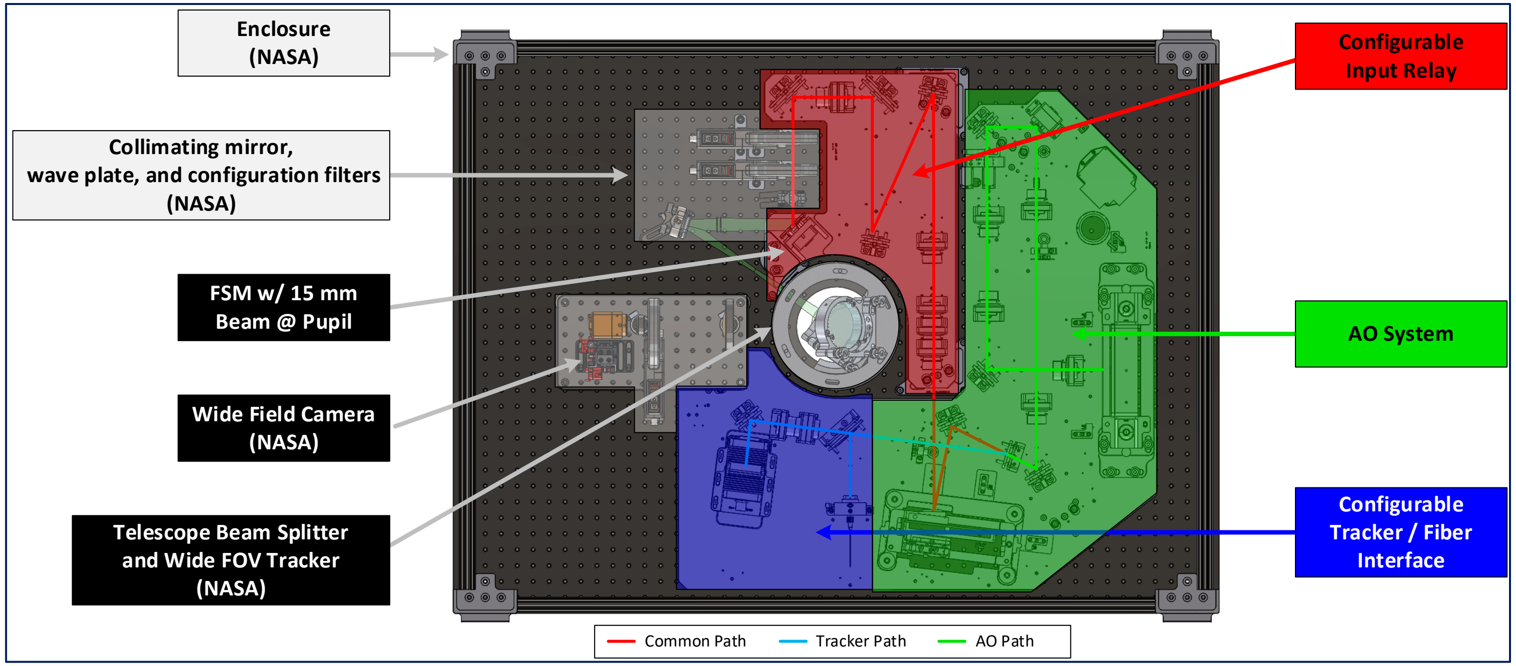


Planned final configuration of the LCOT Free-Space Optical Subassembly

Adaptive Optics

Why Adaptive Optics? Coherent communication formats (as well as Quantum communications) typically must be coupled into a single mode fiber (SMF) for processing. Unfortunately, turbulence induced wavefront error leads to blurring of the light from the downlink so that its image is much larger than the SMF. The wavefront error must be removed using Adaptive Optics (AO), and if it is going to correct while the telescope is slewing to track a LEO spacecraft, it must apply these corrections at a very high rate.

- LCOT procured AO from Guidestar Optical Systems (later acquired by General Atomics)
- Designed to support reception of a downlink from a LEO spacecraft and to allow reconfiguration (filter wheels, relay optics, fiber coupling optics)
- Delivered to GSFC in August 2021
- Underwent extensive testing and characterization in the lab
- Integrated onto port optical bench and tested in vertical configuration in preparation for installation on telescope
- Optical bench will be enclosed, and temperature controlled
- Higher-order correction can be bypassed with only tip-tilt correction implemented



Layout of AO system on LCOT port optical bench (POB)

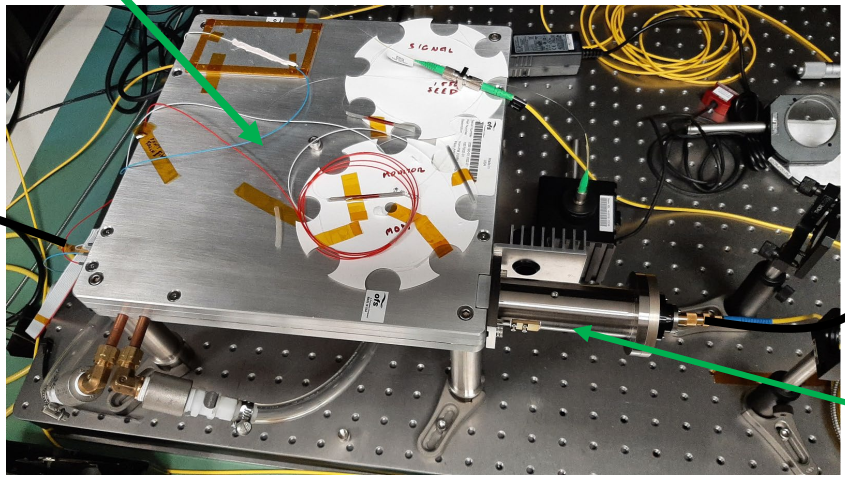
Amplifier Subsystem

- Consists of 3 key functional pieces:
  - The Raman Fiber Laser (RFL) Pump laser (Will be in shelter- provides up to 50W of 1480nm light to pump gain medium in VLMA amplifier Head)
  - The Very Large Mode Area (VLMA) amplifier Head (Will be mounted on 70cm Telescope- can provide >10W amplified signal.)
  - The Optics Train (Attached directly to VLMA- takes free-space output from VLMA and couples it into fiber for transport to transmit telescope)
  - Additionally, we added a safety system to prevent damage to Amplifier due to loss of signal- The 'SCRAMplifier'

RFL pump located in equipment shelter

<15m Armored Conduit fiber for Pump Light

VLMA will be mounted on telescope In dome



Transmit Telescope

Optics Train

Monitor and Control Subsystem (MCS)

MCS is responsible for overall monitor, control and interface of the following LCOT components:

Free Space Optical Subsystem Monitor and Control

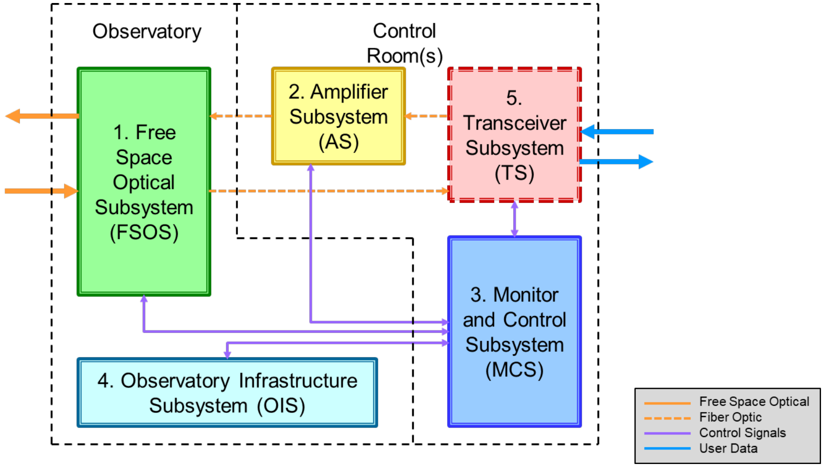
- State Machines, Trackers and Backend opto-electronics for Port/Starboard optical benches (POB and SOB), and Transmit Optical Assembly (XOA)
  - Includes Adaptive Optics Wrapper
- Mount Control and Mount Safety

Observatory Infrastructure Subsystem Monitor and Control

- Atmospheric Monitoring Assembly
- Infrastructure (UPS, Safety related, Environmental)

Amplifier Subsystem Monitor and Control

- Raman Fiber Lasers (RFLs)
- SCRAMplifier/AS safety



Transceiver Subsystem Monitor and Control

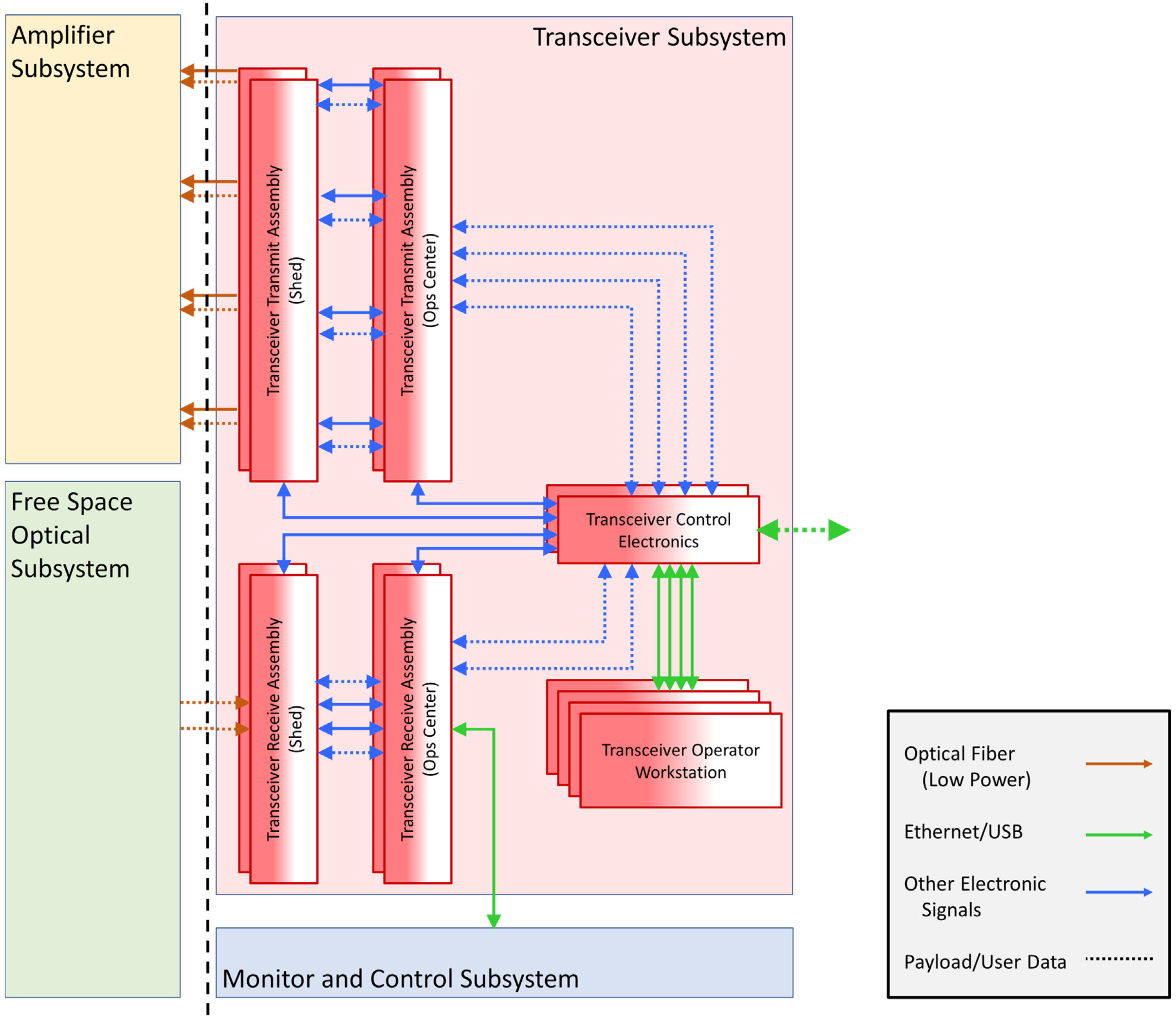
- Send and receive status with customer TS
  - MCS does not directly control TS

General LCOT/MCS Infrastructure

- User Interface Master Monitor and Control - Operator Interface
- Safety Monitor System
- Logging Manager and Reporting Subsystems

Transceiver Subsystem

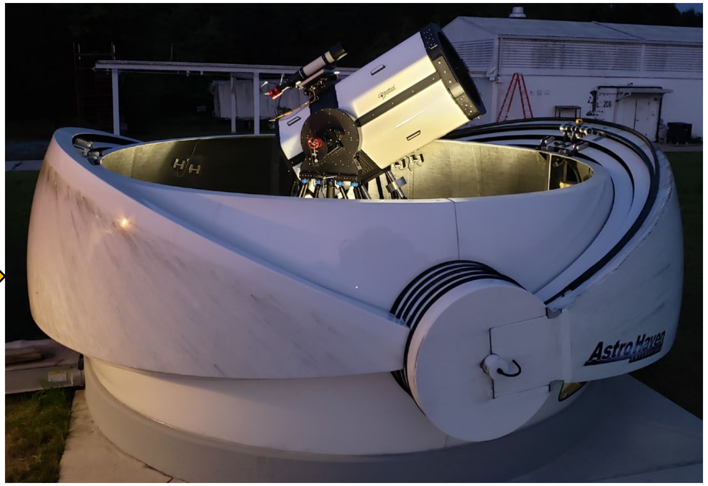
- The image to the right is a notional Transceiver Subsystem (TS) configuration
- Individual TSs will vary as LCOT is transceiver agnostic
  - User TSs may be duplex transceivers, standalone receivers, or standalone transmitters with or without acquisition beacon functionality
- The notional configuration is based on experience on previous programs, and consists of:
  - Electro-Optical Components
  - Electrical Components, e.g. modem
  - Control Electronics
  - Operator Workstations



Observatory Infrastructure Subsystem (OIS)

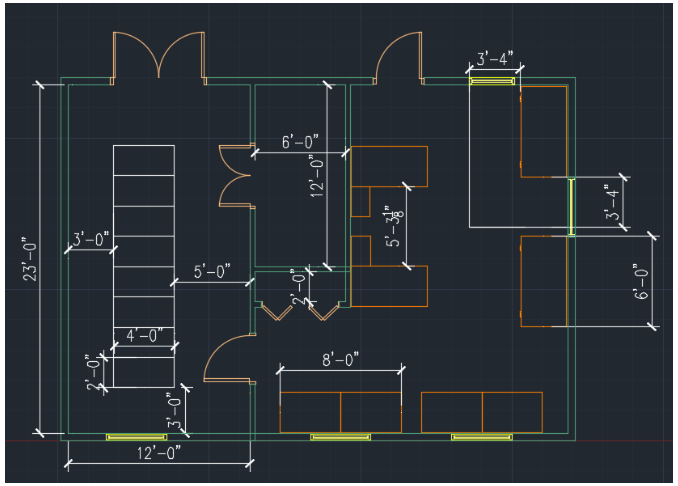
LCOT resources are divided between three structures:

Observatory (*Existing*): Houses the FSOS and components of the Amplifier Subsystem (AS) and Monitor and Control Subsystem (MCS) that need to be on or immediately adjacent to the gimbal.



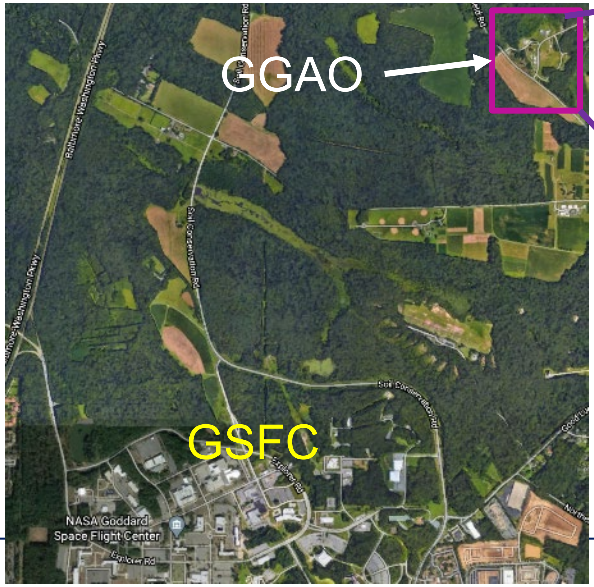
Equipment Shelter (*Existing*): Houses components of the AS, MCS, and Transceiver Subsystem (TS) that need to be within 10m of the gimbal.

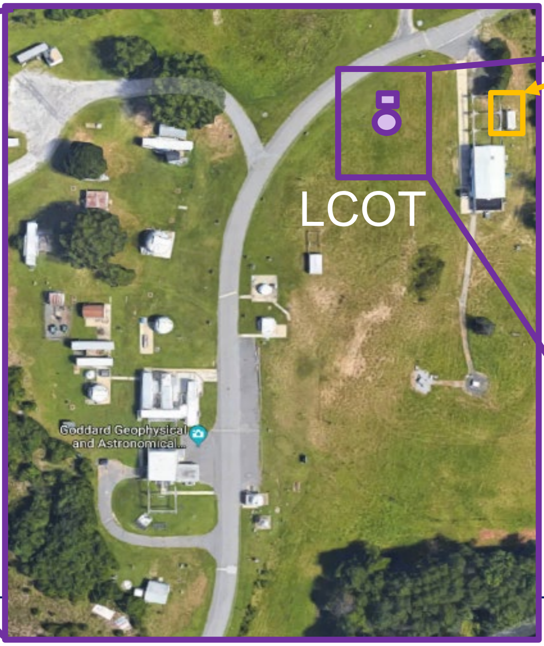
Operations Center (*Planned*): Houses all component that are not location sensitive and provides working space for staff.

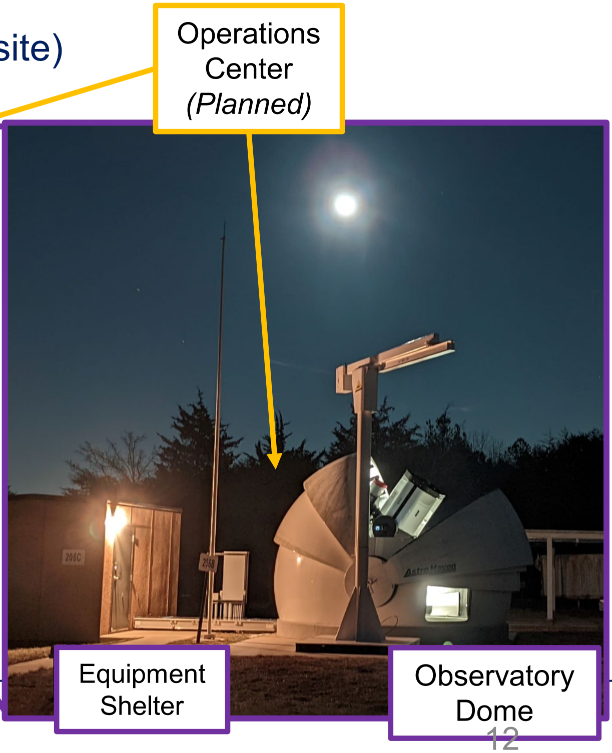


LCOT Location

- In 2018, construction began on the infrastructure for a low-cost demonstration using a small telescope to receive downlink from a LEO satellite
- Located at the Goddard Geophysical and Astronomical Observatory (GGAO) on Goddard Space Flight Center (GSFC) property close to and with direct fiber connection to the GSFC main campus
- 10’x14’ shelter (Equipment Shed) and 16’ diameter dome with isolated concrete pier (Observatory)
  - Dome intentionally sized to house a much larger telescope than we had at the time
- This site provided much of the infrastructure needed for the much more ambitious LCOT facility in the future
  - Supporting LCOT operations will require and Operations Center for personnel and servers
- Site already used for outdoor laser transmissions (Satellite Laser Ranging work already being done on site)







LCOT Capability Milestones

Identified Missions

- LCRD Phase A: Sep 2023
- LCRD Phase B: Apr 2024
- LCRD Phase C: Sep 2024
- O2O: December 2024
- LCRD Comms Demo June 2025

2021	2022	2023	2024	2025	2026

Hardware Readiness

- RTA: Jul 2021
- HPOA: May 2022
- POB: Apr 2023
- AS: Feb 2024
- XOA: Mar 2024
- Subsystem Testing Complete: May 2025
- Fully Integrated: Nov 2025
- Fully Tested: May 2026

Capabilities

- **Rx Passive Tracking** only
- Test imaging capability

- **Rx Fine** Tracking and **Adaptive Optics**
- Tx Gimbal Tracking w/ **10W** Beacon to **GEO**

- Rx Fine Tracking and **Coherent Comms**
- Tx Gimbal Tracking w/ **40W** Signal/Beacon to GEO

- Rx Fine Tracking and Coherent Comms
- **Tx Fine Tracking** w/ 40W Signal/Beacon to **Lunar**

Requires additional/temporary XOA

Limited Capability during LCOT Development

- Non-Coherent **LEO-Lunar** Comms w/**40W** Signal/Beacon
- Coherent **LEO-Lunar** Comms w/**20W** Signal/Beacon

Full Capability

Acronyms
AS: Amplifier Subsystem
POB: Port Optical Bench Assembly
RTA: Receive Telescope Assembly
XOA: Transmit Optical Assembly

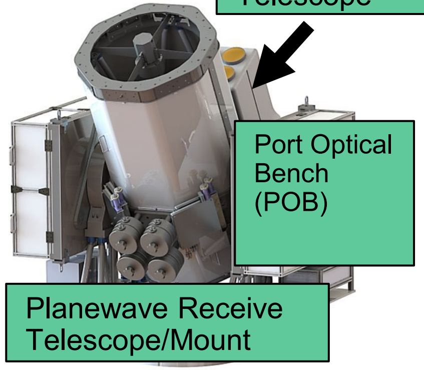
**: Non-Coherent Comms also possible using passive/minimal AO*

System Test / Demo Element Utilization

LCOT Build	b1.0	b2.0	b3.0	b4.0	R1.0
Description	**LCRD Phase A** LCRD downlink with adaptive optics optical bench	**LCRD Phase B** LCRD downlink with SOB utilizing automated WF/NF field-of-view tracking	**LCRD Phase C** LCRD uplink and downlink using XOA, adaptive optics and the LCRD modem	**O2O Demo** O2O uplink & downlink with XOA, POB & RealTOR transceiver	**LCRD Demo** LCOT and OGS-x optical relay via LCRD utilizing LCRD modem
Notional Date	2023	2024	2024	2024	2025
MCS Release	MCS-0.1.0	MCS-0.2.0	MCS-0.3.0	MCS-0.4.0	MCS-0.5.0
Gimbal Control	Manual	Automated	Automated	Automated	Automated
AO Optical Bench (POB)	✓	✗	✓	✓	✓
Non-AO Optical Bench (SOB)	✗	✓	✗	✓	✗
Wide Field Tracking	Manual	Automated	Automated	Automated	Automated
Narrow Field Tracking	Manual	Automated	Automated	Automated	Automated
Temp Beacon &Temp XOA	✓	✓	✗	✗	✗
XOA	✗	✗	✓	✓	✓
LCRD Ground Modem	✗	✗	✓	✗	✓
RealTOR Transceiver	✗	✗	✗	✓	✗

LCOT Experiments- Major Hardware Configuration Changes

Phase A



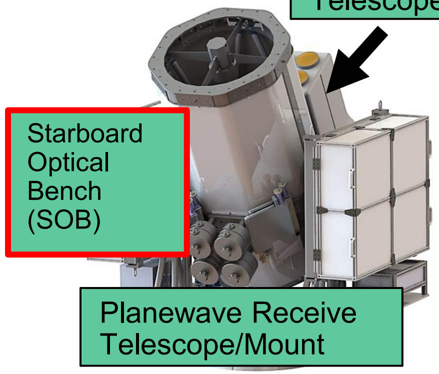
Free Space Optical Subsystem (FSOS)

- Receive (RX) Telescope/Mount
- RX Port Optical Bench (POB)
  - Adaptive Optics System
  - WFOV Cam 
  - **Optical Equipment Control (OEC) for POB:**
    2 RX Focus Wheels
    WF Focus Wheel
    WF Focus Mech.

Amplifier Subsystem (1 channel)

- 1 Raman Fiber Laser (RFL)
- 1 channel SCRAMplifier
- 1 NuPhuton Preamp

Phase B

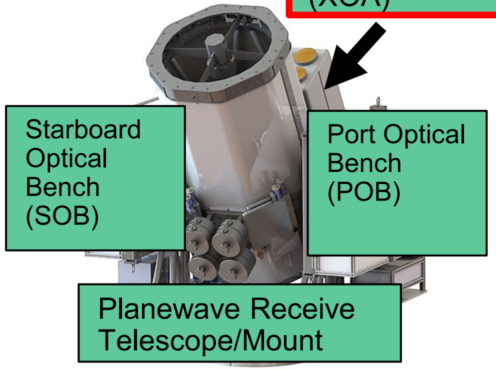


Free Space Optical Subsystem (FSOS)

- RX Telescope/Mount
- **RX Starboard Optical Bench (SOB)**
  - NFOV Cam and Fast steering mirror (FSM)  
  - WFOV Cam 
  - **OEC for SOB:**
    2 RX Focus Wheels
    RX Camera Focus Mech.
    WF Focus Wheel
    WF Focus Mech.

Amplifier Subsystem (1 channel)

Phase C, O2O, LCRD Full



Free Space Optical Subsystem (FSOS)

- RX Telescope/Mount
- RX POB
- RX SOB
- **Transmit Optical Assembly (XOA) – 4 channel**
  - NFOV Cam and FSM  
  - **OEC for XOA:**
    Pending XOA Design

Amplifier Subsystem **(4 channel)**

- **4** Raman Fiber Laser (RFL)
- **4** channel SCRAMplifier
- **4** NuPhuton Preamps

Summary and Path Forward

- Summary
  - Design an optical communication ground system architecture with the flexibility to support a range of use cases while leveraging industry capabilities and collaborate with universities to the maximum extent possible
  - LCOT's multi-disciplinary team is making quick progress to best utilize the funding currently available
  - Further NASA investment is needed to be fully capable of demonstrating SCaN optical communications services

- Path Forward
  - Complete development and implementation for the LCOT-GGAO
    - Complete characterization of Receive telescope and Adaptive Optics
    - Complete procurement of the Transmit telescope and HPOAs
    - Complete software development and testing and install at GGAO
    - Review released Request for Information (RFI) responses:
  - Coordinate experiment and demonstration opportunities with prospective missions
    - Complete Interface Control Document (ICD) between LCOT and User Transceiver Subsystem
    - Identify and refine experiment objectives

- Looking ahead
  - Upon completion of the LCOT-GGAO, perform tech transfer of LCOT design to allow industry, universities, and others to build and deploy LCOT
  - Australian National University (ANU) Collaboration
    - NASA and ANU have a Space Act Agreement to collaborate and share lessons learned on common optical ground terminal components (e.g. Planewave 70-cm receive telescope)
    - ANU optical ground terminal will be located in Canberra. They have plans for a future optical ground network.
    - Goal is to have as much commonality as possible between the LCOT-GGAO and ANU optical ground terminal

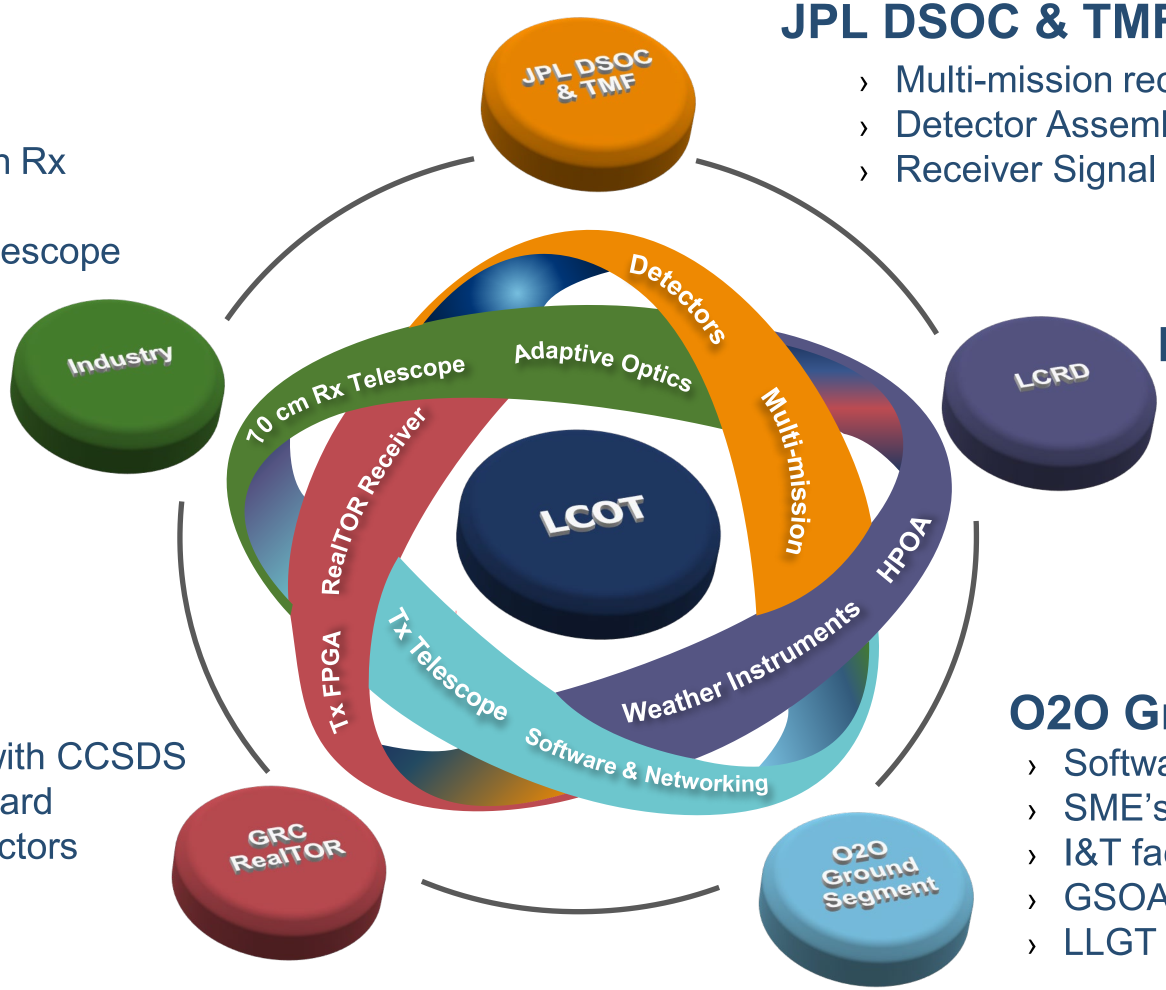
Why LCOT is Low Cost

Industry

- 70 cm Multi-mission Rx telescope
- Multi-mission Tx telescope
- Adaptive Optics
- VLMA HPOA

JPL DSOC & TMF

- Multi-mission receive design concept
- Detector Assembly
- Receiver Signal Processing Assembly



LCRD

- Weather Monitoring Instruments
- Very Large Mode Area (VLMA) High Power Optical Amplifier (HPOA) Design Concept
- Subject Matter Expertise

GRC RealTOR

- RealTOR Receiver
- Transmit FPGA compatible with CCSDS High Photon Efficiency standard
- Quantum Opus SNSPD detectors

O2O Ground Segment

- Software/Networking approach
- SME's
- I&T facilities and equipment
- GSOA & GDE
- LLGT Monitor and control software

LCOT benefits from SCaN's Optical Communications Investments

LCOT Ground Terminal of the Future

LCOT closes Industry's Optical Comm Technology Gaps

LCOT
Multi-mission comparatively low-cost, commercial ground station. Compatible with LCRD, O2O, and ILLUMA-T

ANU
Australasian Optical Ground Station Network

Commercial Entities
Rely on SCaN to build the first multi-mission ground station & provide blueprint of design

Global Optical Network

LCOT enables Quantum Comm

Quantum needs optical ground stations

Planewave reports that other universities are purchasing the same receive telescope to use in quantum comm

LCOT receives many inquiries about its ability to support quantum comm from NASA missions, OGAs and external organizations, such as DCQNet

Acronyms

Name	Definition
ANU	Australian National University
AO	Adaptive Optics
AS	Amplifier Subsystem
CCSDS	Consultative Committee for Space Data Systems
FAT	Factory Acceptance Test
FPGA	Field Programmable Gate Arrays
FSM	Fast Steering Mirror
FSOS	Free Space Optical Subsystem
GDE	Ground Data Element
GEO	Geostationary Orbit
GGAO	Goddard Geophysical and Astronomical Observatory
GSFC	Goddard Spaceflight Center
GSOA	Ground Segment Operations and Analysis
HPOA	High Power Optical Amplifier
ICD	Interface Control Document
IR	Infrared
LCOT	Low Cost Optical Terminal
LCRD	Laser Communications Relay Demonstration
LEO	Low Earth Orbit
LLGT	Lunar Laser Ground Terminal
MCS	Monitor and Control Subsystem
NASA	National Aeronautics and Space Administration

Name	Definition
NFOV	Narrow Field of View
O2O	Orion Artemis II Optical Communications
OEC	Optical Equipment Control
OIS	Observatory Infrastructure Subsystem
POB	Port Optical Bench
PWI	Planewave Instruments
RealTOR	Real Time Optical Receiver
RFI	Request For Information
RPM	Robotic Piggyback Mount
RTA	Receive Telescope Assembly
SCaN	Space Communications and Navigation
SCPPM	Serially Concatenated Pulse Position Modulation
SME	Subject Matter Expert
SMF	Single Mode Fiber
SNSPD	Superconducting Nanowire Single-Photon Detector
SOB	Starboard Optical Bench
TS	Transceiver Subsystem
VLMA	Very Large Mode Area
WFOV	Wide Field of View
XOA	Transmit Optical Assembly

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